Beam-Induced Electron Loading Effects in High Pressure RF Cavities

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APC/Fermilab

All Experimenters' Meeting

Background

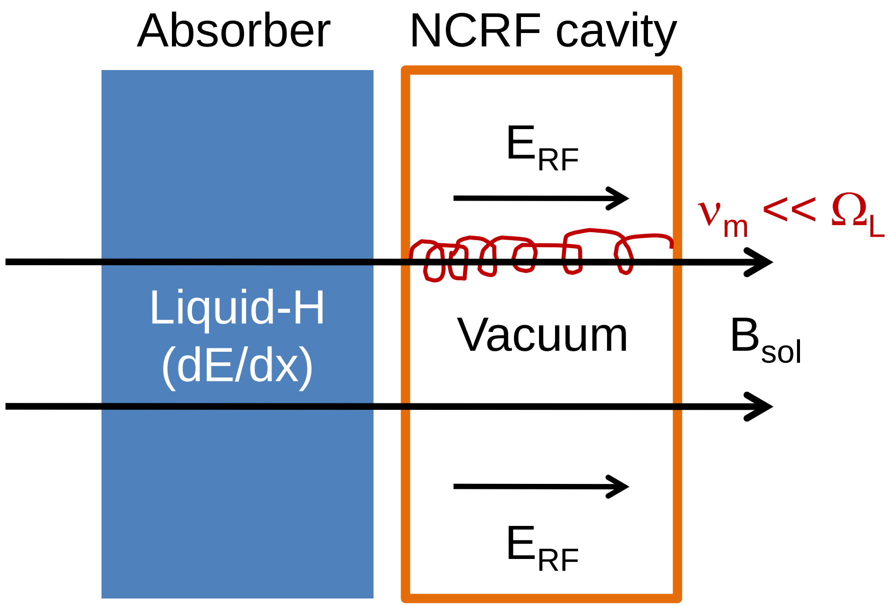
- Muon collider can lead Fermilab back to the energy frontier beyond LHC

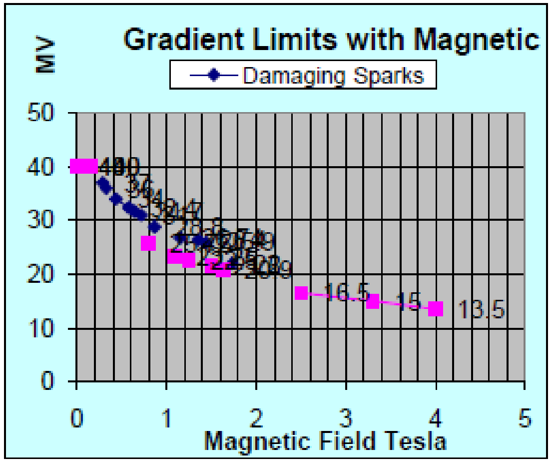
- Key component of the muon collider is ionization cooling channel

- Toughest technical challenge: How to operate RF cavity in the presence of strong magnetic fields

A. Tollestrup's previous AEM talk

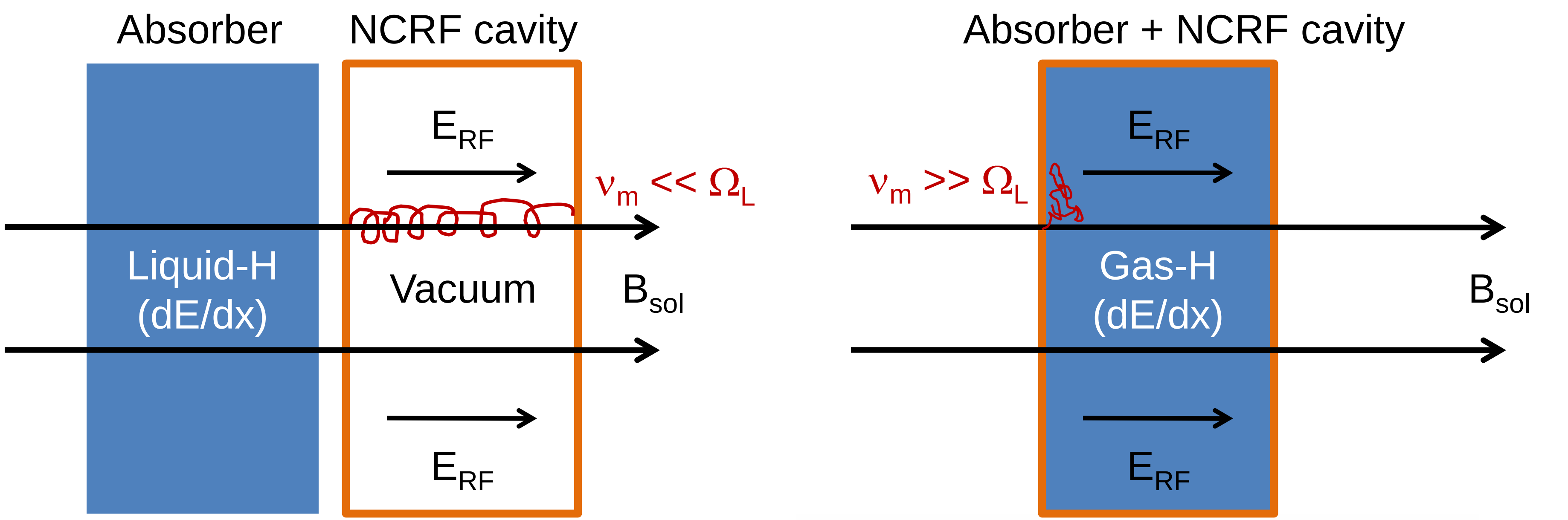
RF Cavities for Cooling Channel

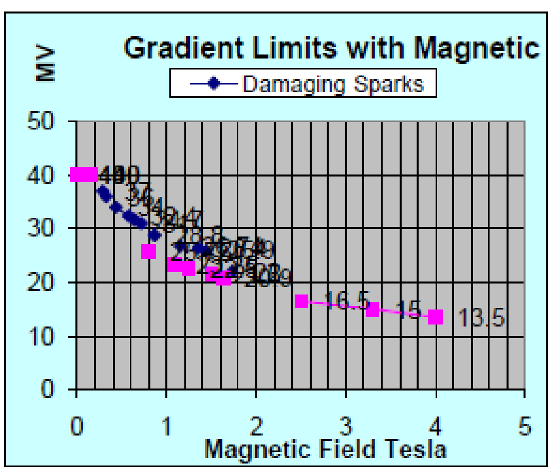




A. Moretti et al.

RF Cavities for Cooling Channel





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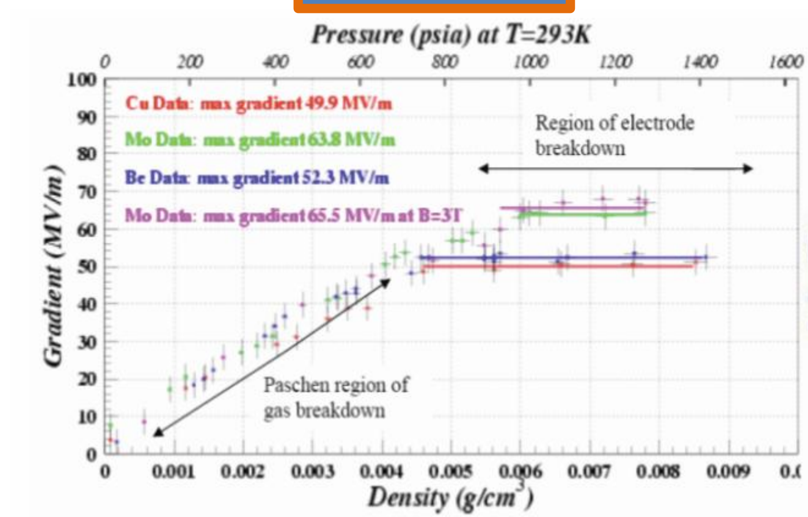
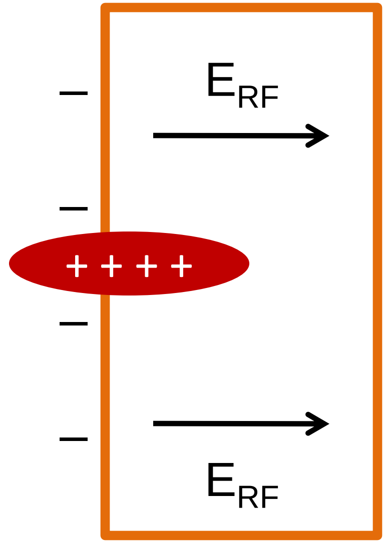


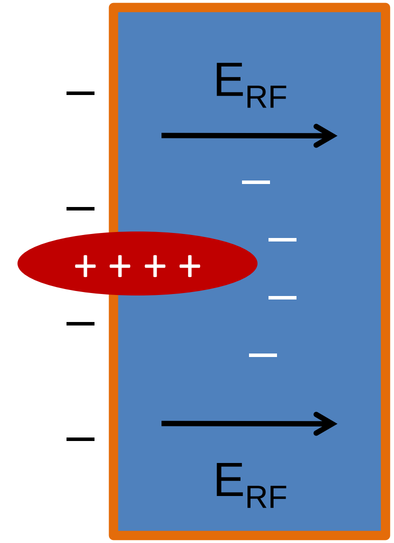
P. Hanlet et al.

What Happens with Beam ?

Evacuated cavity



High pressure cavity

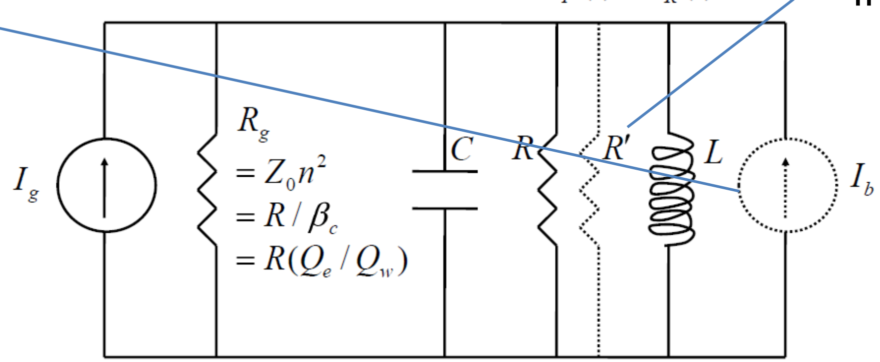


Induced voltage
from beam current

Matched generator

$$V_c(t) = V_g(t) + V_b(t)$$
$$= V_F(t) + V_R(t)$$

Additional shunt resistance
from beam-induced electrons



$$\omega_0 = 1/\sqrt{LC}, \; Q_w = \omega_0 RC$$

Beam Loading Theory 1/2

Step 1: Beam-impact ionization + Ionization by secondary e^-:

$p + H_2 \rightarrow p + H_2^+ + e^-$ $\qquad$ $e^- + H_2 \rightarrow H_2^+ + 2e^-$

$$\boxed{\frac{\Delta n_e}{1\ \text{proton}} \approx \frac{\rho(dE/dx)\Delta s}{W_i(\approx 35\ \text{eV})} \times \frac{1}{(\pi r_b^2 \Delta s)} \sim 1000/\text{cm}^3}$$

Step 2: Most electrons (>90%) are quickly thermalized inside the cavity by elastic and inelastic collisions, and drift with RF until annihilated by recombination or attachment:

$$\boxed{\frac{dn_e}{dt} = S + \cancel{k_i n_g n_e} - \beta_r(T_e)n_e^2 - k_a(T_e,T_g)n_g n_e - \cancel{\frac{D}{\Lambda^2} n_e}} \quad T_e(E/p) \approx \text{const.}$$

$e^- + H_2^+ \rightarrow H + H$

$e^- + H_3^+ \rightarrow H + H + H,\ H_2 + H$

$e^- + H_2\,(v>0) \rightarrow H + H^-$

Beam Loading Theory 2/2

Step 3: Response of plasma electrons to the RF field is described by complex conductivity:

$$\nu_m \approx 2\times 10^{11}\, p[\text{psia}]$$

$$\sigma_{DC} = \frac{n_e e^2}{m_e \nu_m}$$

$$\boxed{\sigma = \sigma_{DC}\left(\frac{\nu_m^2}{\nu_m^2+\omega^2} - j\frac{\omega}{\nu_m}\frac{\nu_m^2}{\nu_m^2+\omega^2}\right)}$$

$$\boxed{\Delta\left(\frac{1}{Q}\right) \approx \frac{\int_V \frac{1}{2}\sigma_{DC}(r)E_0^2(r,z)dV}{\omega\int_V \frac{1}{2}\varepsilon_0 E_0^2(r,z)dV},\quad \Delta f_0 \approx \frac{f}{2}\cancel{\left(\frac{\omega}{\nu_m}\right)}\times\Delta\left(\frac{1}{Q}\right) > 0}$$

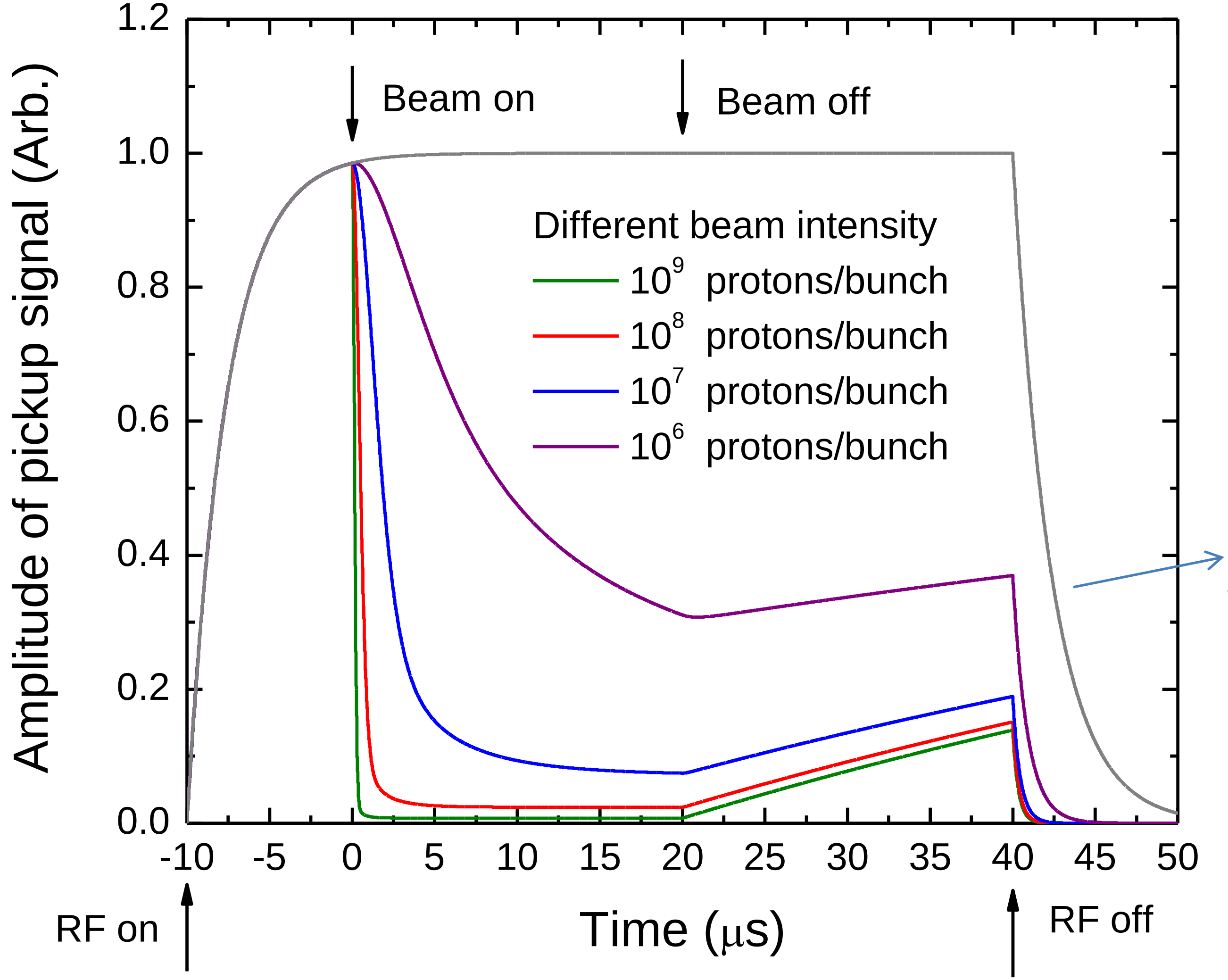
Step 4: Equivalent circuit model:

$$\boxed{\begin{gathered} V_c = V_F + V_R \\ \left\{\frac{d^2}{dt^2} + \omega_0\left(\frac{1}{Q_L} + \Delta\left(\frac{1}{Q}\right)\right) + \omega_0^2\right\}V_c = 2\frac{\omega_0}{Q_e}\frac{dV_F}{dt} - \frac{\omega_0}{2}\left[\cancel{\frac{R}{Q}}\right]\cancel{\frac{dI_b}{dt}} \end{gathered}}$$

Additional damping term by beam-induced electrons

Additional driving term by beam itself

Expected Results

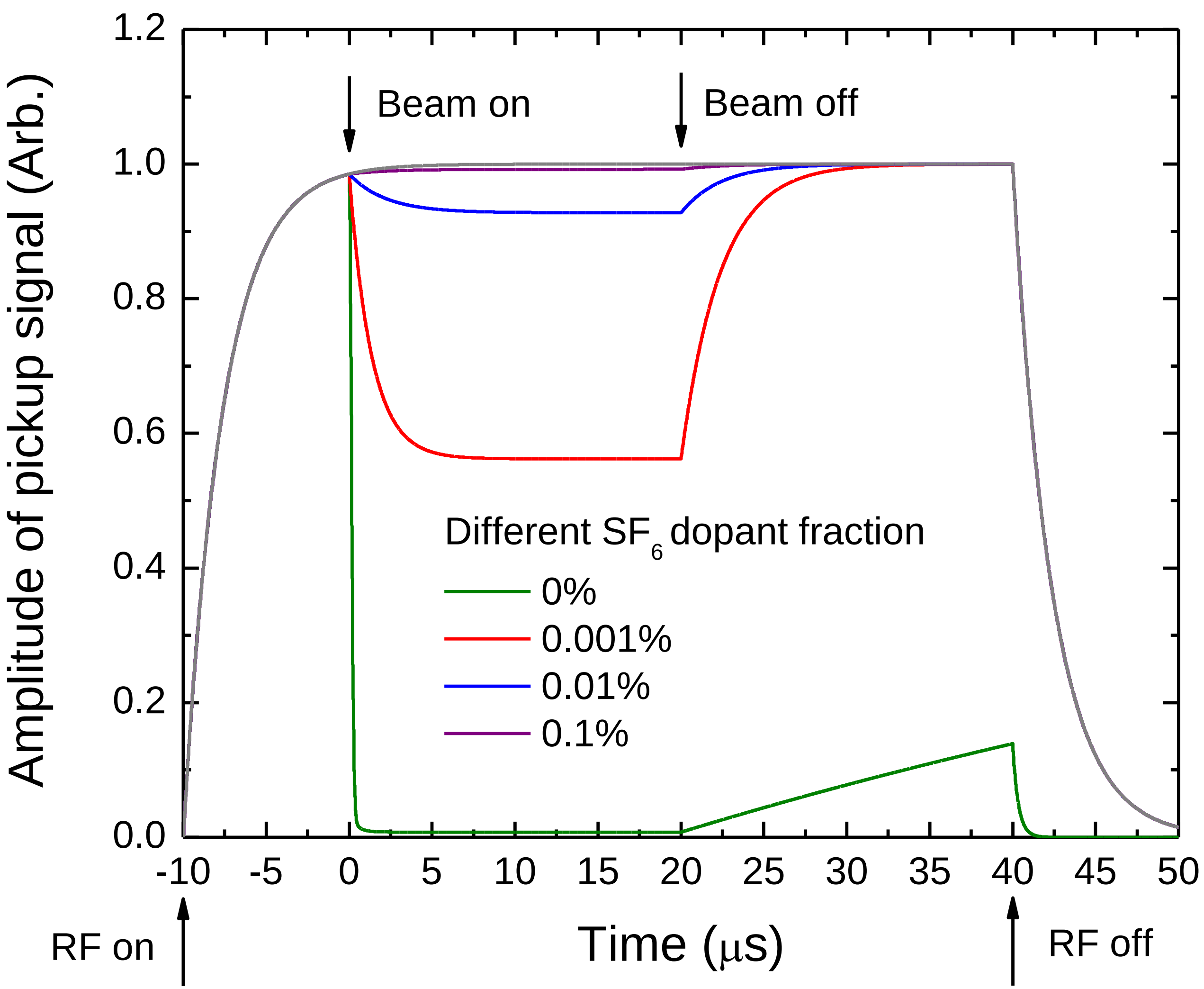


1. Rapid decay of pickup signal according to the ionization rate

2. Saturation level and recovery rate determined by the recombination rate

Gray line: normal signal without beam

What is the Solution ?

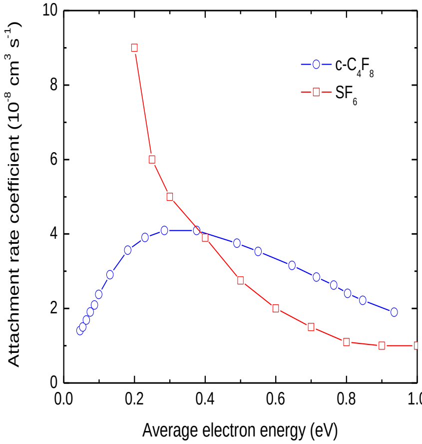


1. Much higher recombination rate than expected due to H_3^+, H_5^+,H_7^+,…etc

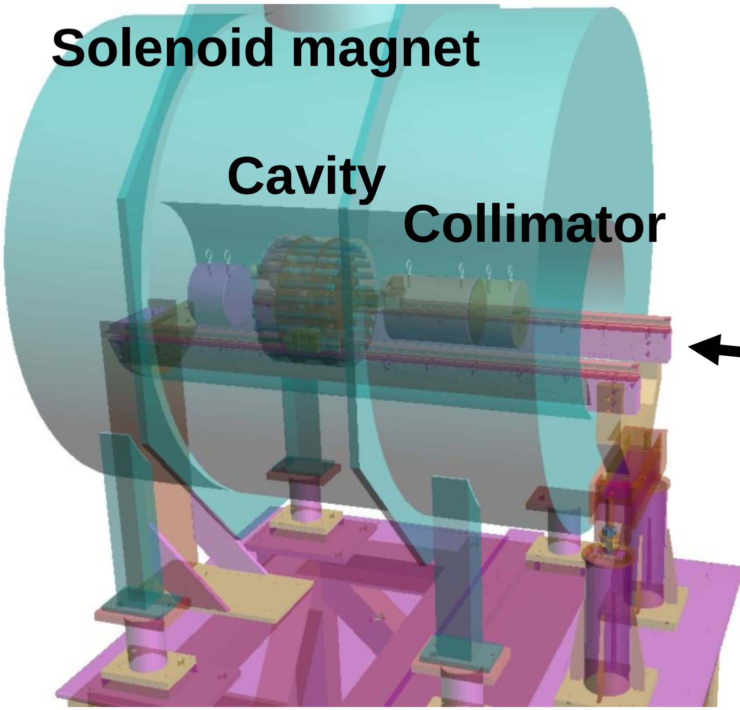
2. Use of a electronegative gas:

$e^- + SF_6 \rightarrow SF_6^-$

$e^- + SF_6 \rightarrow SF_5^- + F$



Beam Test



Beam

MTA Beamline

Beam test of the high pressure RF cavity will be a critical step for muon accelerator R&D program (MAP)

Thanks to the collective work among APC/AD/TD, we’re almost ready (Fall 2010) to do the beam test !